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ABSTRACT

A theoretical model is presented for calculating the heating and hydrodynamic expansion of the F-layer of the ionosphere due to an incident radiowave. We find that the greatest effects occur for transmitter frequencies just above the critical frequency of the F-layer. Using a power aperture product of 10^4 megawatt-meter^2, which corresponds to a projected experiment by ESSA at Boulder, Colorado, we find a maximum increase in the electron temperature at the peak of the F-layer of about thirty percent with a reduction in the electron density of about ten percent. The time scale for achieving the density changes is predicted to be about one-half hour to an hour.

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1. INTRODUCTION

There has been considerable interest in the problem of heating the electrons in the F-region of the ionosphere by radiowave propagation. Ginzburg and Gurevich [1960] and Gurevich [1967] in the Soviet Union have published extensively on this problem and Farley [1963] in the United States has also addressed the problem. In the work done to date steady-state conditions have been assumed and, in addition, pressure equilibrium as a function of altitude has been assumed for the heated plasma. These approximations are reasonably valid for equatorial latitudes where the earth's magnetic field lines are more or less horizontal. With horizontal field lines the heated plasma can equilibrate horizontally with the ambient unheated plasma. In northern latitudes where the earth's magnetic fields are more nearly vertical, it would appear that the assumption of pressure equilibrium is not appropriate. Indeed, the cross field drift of the plasma due to lateral pressure gradients is so slow (less than 1 cm/sec) that the heated plasma is essentially confined to expand up and down along the field lines. We are interested in this geometry since ESSA plans to conduct experiments at Boulder, Colorado this fall in modifying the normal F-layer.

In the following section a theoretical model is described which approximates the hydrodynamic motion as being in one dimension along the field lines. Thermal conduction of the heated electrons is accounted for as well as the viscous drag imposed on the ions by the

neutral particles of the ambient atmosphere. The neutrals are treated as a heat sink at the ambient temperature of the ionosphere.

The partial differential equations representing the conservation equations were numerically integrated on a high speed computer. The results of the calculations are shown in Section 3 where we examine the temperature rise and the rate of expansion of a model F-layer as a function of the transmitter frequency. In the calculations we have assumed a power-aperture product of 10^4 Megawatt meter^2, continuous wave, appropriate to the ESSA experiment. We find that a maximum heating rate is obtained for a frequency which almost gives a null for the dielectric constant of the ordinary ray. This result differs from that of Gurevich [1967] who finds an optimum heating frequency at about twice the critical frequency. This difference may be traced to the fact that Gurevich maintains a constant beam width as the transmitter frequency is varied. That is, Gurevich treats the problem of a fixed incident flux on the ionosphere. This can be accomplished by changing the size of the antenna aperture as a function of frequency or by varying the power as the frequency changes. We have considered a somewhat more practical example of constant aperture size which corresponds to the planned experiment. Therefore, for frequencies well above the critical frequency, we find that the heating rate is essentially independent of frequency. However, as one reduces the frequency and approaches the null in the dielectric constant, an enhancement of the heating rate occurs. As an example of this we will present the results of a heating program which maintains the transmitter frequency to within 1% of the nulling

frequencies as a function of time.

We will begin by describing the theoretical model and then will present the numerical results.

2. THEORETICAL MODEL

We imagine that an antenna is directing radiowave energy into the ionosphere and parallel to the earth's magnetic field lines. At the latitude of Boulder, Colorado this would require a pointing angle of about 22° from the zenith, the dip of the magnetic field lines being 68° at that latitude. As the RF energy heats the plasma of the ionosphere, the plasma, of course, tends to expand. We observe that the magnetic pressure is far greater than the plasma pressure and the cross-field drift of the plasma due to the pressure gradient is extremely small. Therefore, the expansion of the plasma will be mainly upwards and downwards along the field lines. Thus, the familiar approximation of pressure equilibrium [Farley, 1968; Gurevich 1967] is not appropriate and we find it convenient to numerically integrate the conservation equations, thereby investigating the transient approach to steady-state conditions. Since we do not expect unusually large departures from ambient conditions, we will consider a perturbation theory approach as outlined in the following.

A. Momentum Equation. We consider a macroscopic velocity of the plasma and write the momentum equation as

$$\rho \frac{Du}{Dt} + \frac{\partial \delta p}{\partial X} + \rho \, \nu_{io} u + \delta\rho \, g \sin\psi = 0, \qquad (1)$$

where the plasma density ρ is

$$\rho = m^+N^+ + m^-N^- = (m^+ + m^-)N, \qquad (2)$$

m^+ and m^- are the ion mass and electron mass, respectively, N is the electron number density,

$$\delta p = p^+ - p_a^+ + p^- - p_a^- \qquad (3)$$

where "+" and "-" denote quantities referring to ions and electrons respectively, and the subscript "a" denotes ambient values. The term $\rho\nu_{io}u$ approximates the momentum exchange to the ambient neutral particles, ν_{io} being the ion-neutral collision frequency. The last term in Eq. (1) is due to the external force of gravity, where g is the acceleration of gravity, ψ is the dip angle of the earth's field and $\delta\rho$ is the departure of the plasma density from ambient. The quantity X is the distance along the field line and is related to altitude z by

$$X \sin\psi = z. \qquad (4)$$

Finally, D/Dt is the Lagrange time derivative and the coordinate X is related to u by,

$$u = \frac{DX}{Dt}. \qquad (5)$$

B. Conservation of Mass. Conservation of mass in the plasma is given by

$$\rho dX = \rho_a dx \equiv dM \tag{6}$$

where M is the usual mass variable and x is the value of X at t=o.

C. Conservation of Energy. We treat the electron gas and the ion gas separately thereby accounting for possible differences in the electron and ion temperatures. If we define the specific energy of the two gases by

$$E^{\pm} = \frac{3}{2}\frac{\theta^{\pm}}{m^{\pm}}, \tag{7}$$

where $\theta^{\pm}$ is the ion (electron) temperature in energy units, we can write the partial differential equations expressing energy conservation as

$$\frac{DE^-}{Dt} + p^- \frac{D}{Dt}\left(\frac{1}{m^- N}\right) = \frac{1}{m_- N}\left[Q - L + \frac{\partial}{\partial X} K \frac{\partial \theta^-}{\partial X}\right], \tag{8}$$

where K is the coefficient of heat conduction

$$K = 3N\theta^-/(m^- \nu^-), \tag{9}$$

and L denotes the loss of energy by electrons to ions and neutrals.

Electrons lose energy to both nitrogen molecules and atomic oxygen. The electron energy loss rate to nitrogen molecules arises

from rotational excitation [Mentzoni and Row 1963]. However, a perhaps dominant loss mechanism in the F-layer has been identified by Dalgarno and Deggs [1968]. This energy loss mechanism arises from transitions among the fine structure levels of atomic oxygen and is induced by electron impact. We assume that energy loss to ions proceeds by classical elastic scattering. Schematically, we can represent the loss term by

$$L = \frac{3}{2} N \nu_{ei} \delta_{ei} (\delta\theta^- - \delta\theta^+) + \frac{3}{2} N \nu_{eo} \delta_{eo} \delta\theta^- + \frac{3}{2} N (\nu\delta)_{\substack{\text{atomic} \\ \text{oxygen}}} \delta\theta^- \qquad (10)$$

where the last term represents the energy loss due to atomic oxygen*. The quantity ν_{ei} is the electron-ion collision frequency, ν_{eo} is the electron neutral collision frequency, δ_{ei} and δ_{eo} are the average, fractional energy loss per collision for electrons colliding with ions and neutrals, respectively and $\delta\theta^{\pm}$ is the departure of the ion (electron) temperature from ambient.

The quantity Q denotes the energy source due to the RF wave heating. Q depends on the flux of energy in the wave,

$$F = \frac{PG}{4\pi X^2} , \qquad (11)$$

where P is the power of the transmitted energy and G is the antenna gain,

$$G \simeq \frac{4}{\varphi^2} = \frac{16\ D^2}{\lambda^2} = \frac{16\ D^2 f^2}{c^2} , \qquad (12)$$

*See Appendix for interpolation formulae representing physical processes.

D is the dish diameter, f the transmitter frequency and φ the half angle of the beam width.

We will consider energy deposition by the ordinary ray of the magneto-ionic waves that propagate in a plasma. For the longitudinal mode (propagation along the magnetic field) Q is approximately given by,

$$Q = \frac{F}{c} \frac{\omega_p^2 \nu A}{(\omega + \omega_L)^2 \epsilon^{\frac{1}{2}}} \left(\frac{\text{ergs}}{\text{cm}^3 \text{sec}}\right) \tag{13}$$

where ω_p is the usual plasma angular frequency, ν is the electron collision frequency (assumed small compared to the wave angular frequency ω),

$$\epsilon = 1 - \frac{\omega_p^2}{\omega(\omega + \omega_L)} \tag{14}$$

and

$$\omega_L = \frac{eB}{mc} , \tag{15}$$

where B is the magnetic field strength and the attenuation A is given by

$$A = \exp \left[- \frac{1}{c} \int_0^X \frac{\omega_p^2 \nu \, dX}{\epsilon^{\frac{1}{2}}(\omega + \omega_L)^2}\right] . \tag{16}$$

It is evident that for high frequencies. $\omega >> \omega_p$, the heating rate is essentially independent of frequency. However, as ω approaches the penetration frequency, an enhancement in the heating rate takes place.

For the ion gas we write

$$\frac{DE^+}{Dt} + p^+ \frac{D}{Dt}\left(\frac{1}{m^+ N}\right) = \frac{3}{2} N \nu_{ei}\delta_{ei}(\delta\theta^- - \delta\theta^+)$$

$$- \frac{3}{2} N \nu_{io} \delta\theta^+. \tag{17}$$

This system of partial differential equations was converted to a system of coupled finite difference equations using the standard techniques. The heat conduction was treated explicitly.

A series of exploratory calculations were run for various radiowave frequencies and for a frequency which was continuously adjusted to be at one-percent above the frequency which nulls the dielectric constant ϵ as given by Eq. (14). The results of these calculations are presented in the next section.

3. NUMERICAL RESULTS

In the numerical results to be described we assumed a neutral composition as given by the CIRA 1965, Model 5, hour 12. Figure 1 shows the neutral composition and temperature as a function of altitude. The electron density as a function of altitude is shown in Fig. 2 [W. H. Hooke, ESSA, Private Communication]. In the calculations we assume that a megawatt of average power arrives at an altitude of 150 km. Under daytime conditions this implies that considerably more power is launched from the ground due to D-region absorption. Under nighttime conditions, D-region absorption is essentially absent and although the neutral particle densities are appropriate to noon conditions, the nighttime run of the concentrations are at times typical to those shown in Figs. 1 and 2. Thus, we may consider the calculations to be presented as representative of conditions resulting from a one megawatt average power ground transmitter with an assumed aperture of 10^4 square meters under nighttime conditions. For simplicity we assume the electron and ion temperatures are equal to ambient, an assumption more appropriate to nighttime conditions.

In the numerical work we took the ionosphere as extending from 150 km to 800 km. For boundary conditions we assumed ambient temperature and pressure were maintained on the top and bottom of the ionosphere. Ten-kilometer zone sizes were assumed.

The relaxation times for electron cooling due to collisions with ions, neutral molecules and atomic oxygen are shown in Fig. 3 under various assumptions. In a series of exploratory calculations done

for the purpose of investigating the radiowave frequency sensitivity, we assumed electron energy loss by elastic collisions to atomic oxygen and assumed a constant fractional energy loss per collision with molecules at 10^{-3}. The cooling times under these simplified assumptions are also shown on the figure. The electron-neutral collision frequency was taken from Mentzoni and Row [1963]. Also shown on the figure are the cooling times for electron cooling by rotational excitation of molecular nitrogen, fine structure transitions in atomic oxygen and electron-ion cooling assuming elastic collisions with atomic ions. The Appendix provides a list of interpolation formulae used to represent the various physical processes.

As stated previously, a series of exploratory calculations investigating the radiowave frequency dependence of the plasma heating and expansion process were performed. The results are shown in Figs. 4 and 5.* The maximum heating takes place near the F-layer peak. Figure 4 shows the fractional change of the electron temperature as a function of time at an altitude of 300 km and for frequencies of 10, 7, 6.35 MHz and for a wave frequency that stayed tuned to within one percent of critical. That is, to a frequency such that $\epsilon = .01$. The required frequency change as a function of time is indicated on the figure. Evidently the electron temperature rises to a plateau in a rather short time ($\sim$ 1 min). On the other hand, the rate of expansion of the plasma is quite slow as indicated in Fig. 5. We attribute this

*In these calculations we assume a magnetic field line dip of 68°, appropriate to Boulder, Colorado. However, in order to assure penetration of the wave, we assume the beam is directed vertically upward.

to the drag on the ions induced by the neutral particles. According to this model, changes in electron density take place over a time span of tens of minutes as contrasted to electron temperature changes which take place over a time span of tens of seconds.

As a final exploratory calculation we used the loss mechanisms from Mentzoni and Row [1963] and Dalgarno-Degges [1968]. The model was idealized to the extent that we assumed vertical field line geometry so that the magnetic field and the axis of the antenna beam were orthogonal to the layers of stratification of the ionosphere. Again, we varied the wave frequency to be within one percent of critical.

Figure 6 shows the fractional change in electron temperature as a function of time for the indicated altitudes. In all cases the ion temperature did not deviate appreciably from the initial ambient value. Figure 7 shows the electron density changes with time. Although the numerical calculations were not run to a final steady-state it is evident that reductions in electron densities of the order of 10 to 15 percent may be expected but that steady-state conditions would not be achieved for times of thirty minutes to one hour.

An interesting feature of the calculations which might be susceptible to experimental verification in the predicted behavior of the velocity of the expanding plasma. When the beam is first turned on, a weak shock is generated in the F-layer peak and the shock propagates up (and down) through the ionosphere. Figure 8 shows the velocities generated at the indicated altitudes. We find very small

downward velocities ($\sim$ 1 m/sec) at 250 km. (The neutral drag inhibits the motion.) But above the F-layer peak, where the neutral drag is much smaller, the upward velocities reach levels of 20 to 60 m/sec as indicated. There may be some possibility of detecting these motions by Doppler techniques.

4. DISCUSSION

The results of these model calculations show that changes in the normal F-layer electron density by factors of a few are probably not obtainable at the power-aperture level (10^4Mω · m^2) to be used in the ESSA experiment. Changes of this order of magnitude have been suggested in the literature. However, if the Dalgarno-Degges [1968] atomic oxygen cooling mechanism is effective then one will be forced to higher power-aperture products, even when following the critical frequency to within one percent.

Another interesting feature of the calculations is the rather slow time scale with which even the modest 10 percent reductions in electron density are obtained. This is due, of course, to the viscous drag by the neutrals on the expanding plasma. This treatment of the plasma-neutral interaction is only approximate. However, for some forms of molecular forces this form of the drag term is exact [Holway 1965]. In any event, it would seem that one must be prepared to heat the ionosphere for times of the order of tens of minutes before substantial reductions in electron density can take place.

There must be one final caveat. We have assumed non-dispersive propagation, i.e., the effects of refraction, as the electron density changes, have been ignored. The possibility of self-focusing for horizontal field geometry has been discussed [Litvak 1968], again in the steady-state approximation. In our case of near vertical field geometry, refraction effects may be expected due to the shape of the antenna beam. The electron heating and hence the rate of plasma

expansion along the field lines is greatest at the center of the beam and decreases as one moves away from the beam axis. This effect produces a lowering of the electron density which essentially reflects the antenna beam shape. It is easily seen that an electron density of this structure, lowest at the center and increasing as one leaves the beam axis, leads to a self-focusing of the electromagnetic energy. Crude estimates suggest that this could be an important effect. The ESSA experiment will provide both in situ measurements of ionospheric electron cooling rates as well as a possible demonstration of self-focusing of electromagnetic waves in the ionosphere.

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APPENDIX

FORMULAE FOR PHYSICAL PROCESS

Electron-ion collision frequency:

$\nu_{ei} = 3\ 10^{-5}\ N/\theta^{3/2}\ \mathrm{sec}^{-1}$ (θ is the electron temperature in electron volts).

Electron-neutral collision frequency:

$\nu_{eo} = 1.95\ 10^{-7}\ N_o\ \theta\ \ \mathrm{sec}^{-1}$ (N_o is the neutral particle density).

Ion- neutral collison frequency:

$\nu_{io} = 6.4\ 10^{-9}\ N_o\ \theta^{+}\ \mathrm{sec}^{-1}$ (θ^{+} is the ion temperature in electron volts).

Fractional energy loss for electron-molecule collisions:

$\delta_{eo} = \frac{10^{-5}}{\theta^{3/2}}$ (θ is the electron temperature in electron volts. This formula is a fit to the data in Mentzoni and Row [1963].

Loss rate to atomic oxygen:

$(\nu\delta)_{\substack{\text{atomic}\\ \text{oxygen}}} = 2.2\ 10^{-12}\ [O]/\theta_a\ \mathrm{sec}^{-1}$.

(θ_a is the ambient air temperature in electron volts and [O] is the atomic oxygen concentration. This is a rough fit to the data in Dalgarno and Degges [1968].

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FIGURE CAPTIONS

Fig. 1. - Neutral composition as a function of altitude. (CIRA 1965, Model 5, 12 hours).

Fig. 2. - Ambient electron density as a function of altitude.

Fig. 3. - Electron cooling times as a function of altitude.

Fig. 4. - Fractional electron temperature change at 300 km altitude as a function of time for the indicated frequencies.

Fig. 5. - Fractional electron density change at 300 km altitude as a function of time for the indicated frequencies.

Fig. 6. - Fractional electron temperature change as a function time for the indicated altitudes. The radiowave frequency was continuously kept within 1% of the critical frequency as indicated.

Fig. 7. - Fractional electron density change as a function of time for the indicated altitudes. The radiowave frequency was continuously kept within 1% of the critical frequency.

Fig. 8 - Velocity of the expanding plasma as a function of time for the indicated altitudes. The radiowave frequency was continuously kept within 1% of the critical frequency.

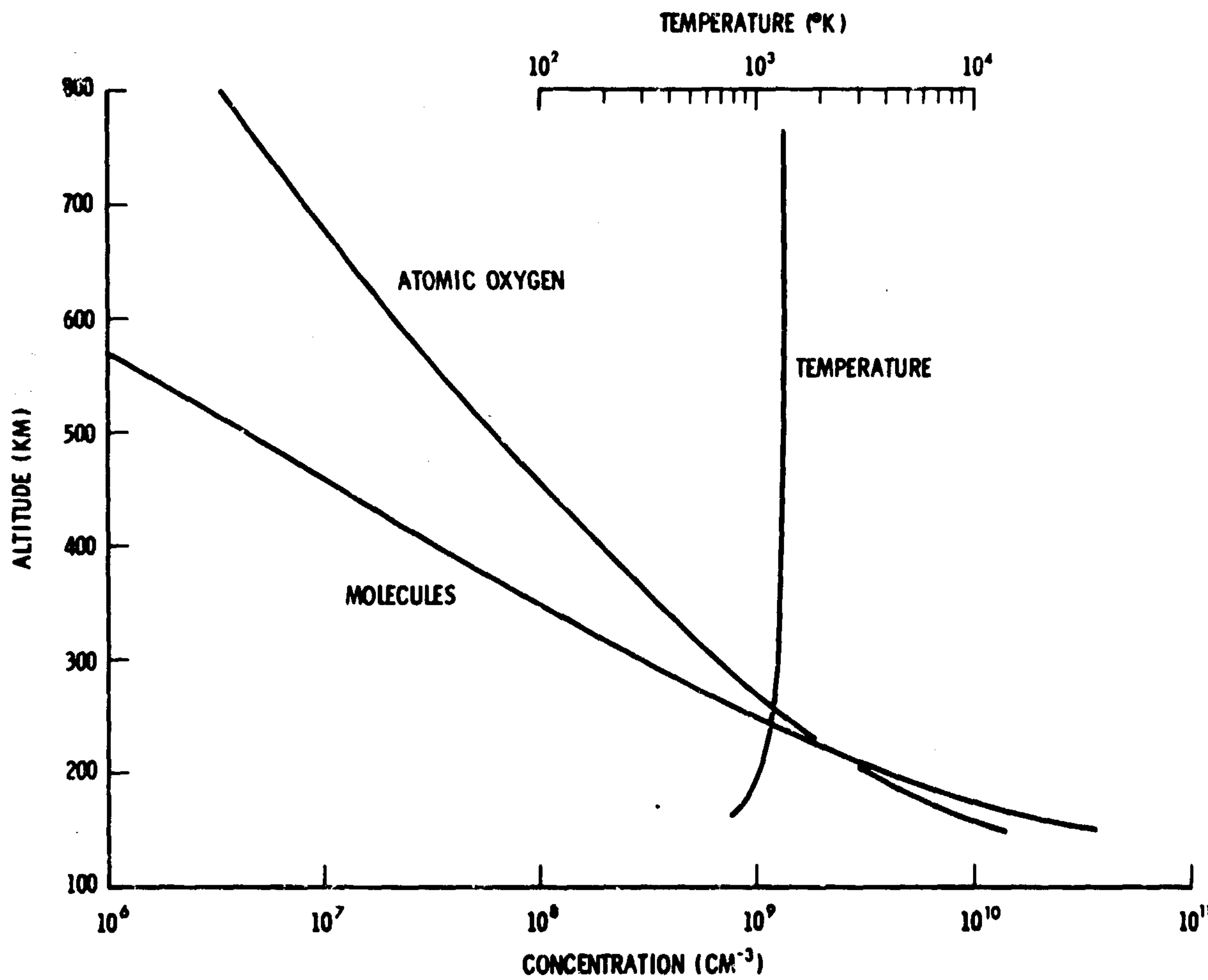

Fig. 1—Neutral concentration as a function of altitude

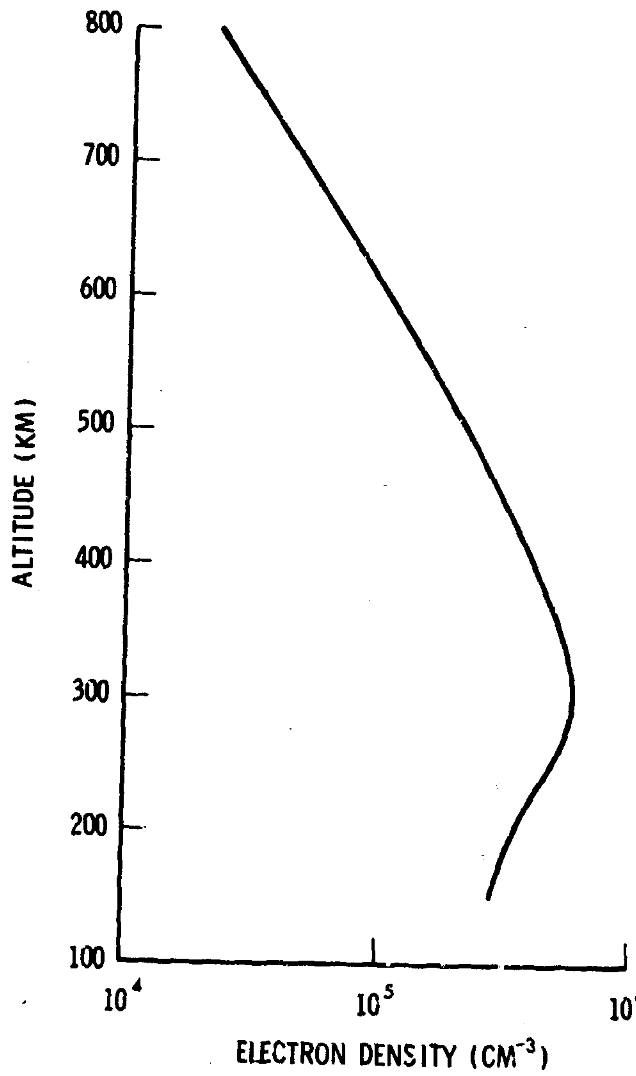

Fig. 2—Electron density as a function of altitude

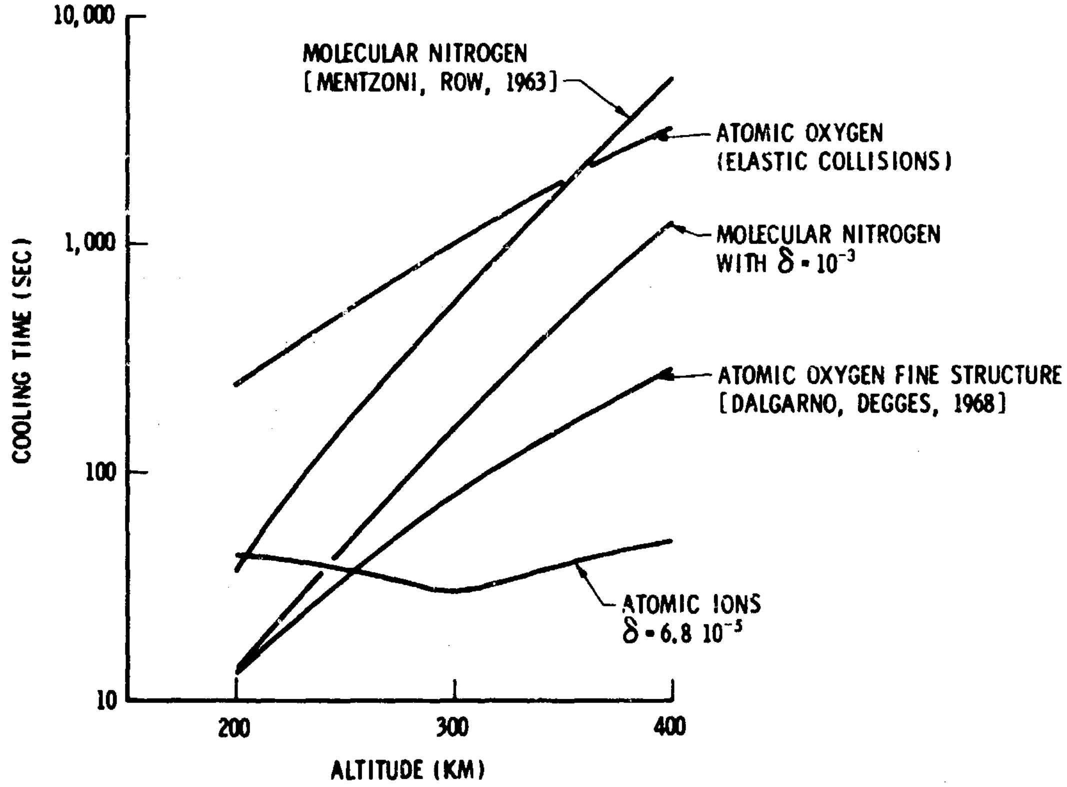

Fig. 3—Electron cooling time as a function of altitude for the indicated processes

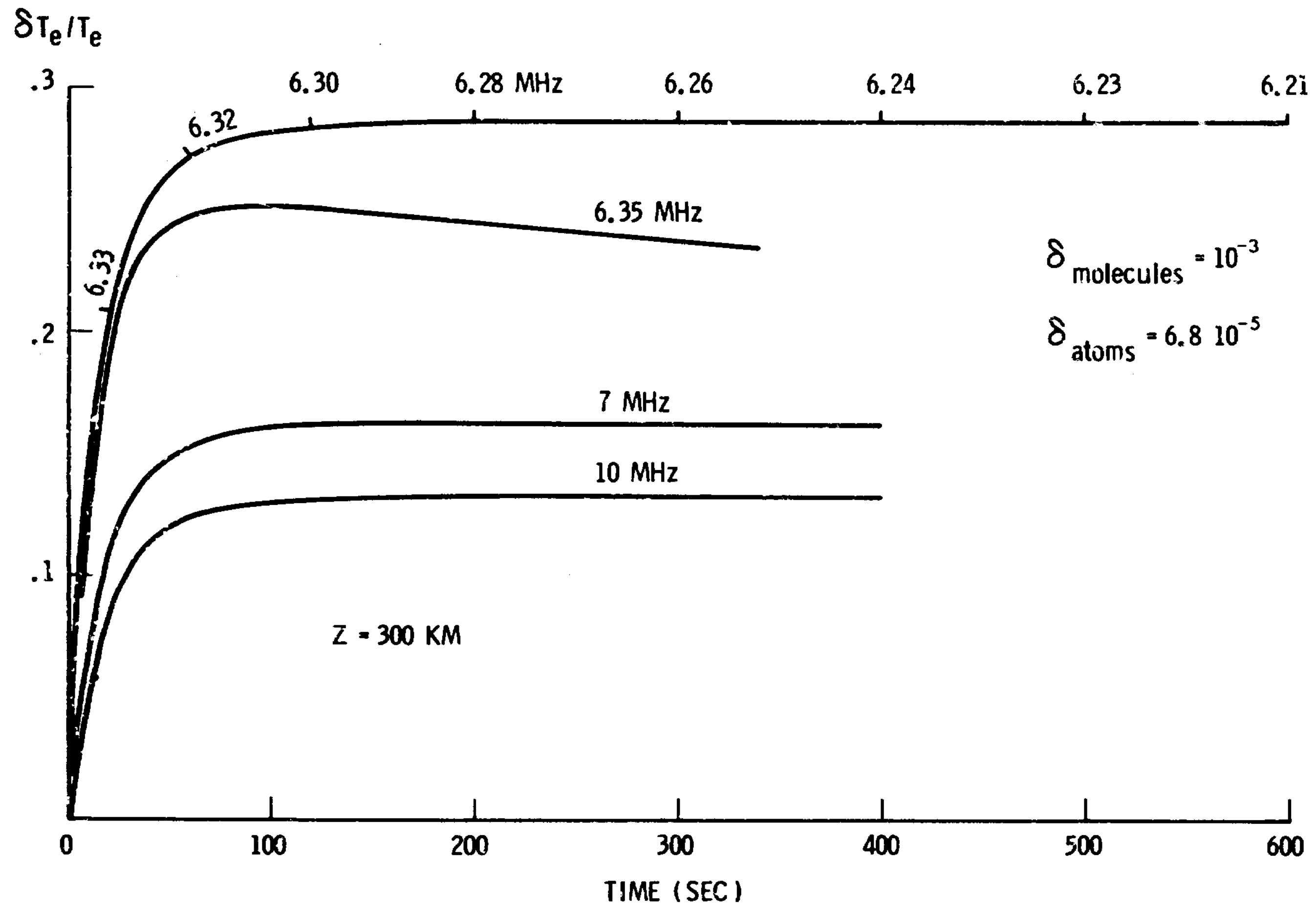

Fig. 4—Fractional electron temperature increase as a function of time for the indicated radiowave frequencies

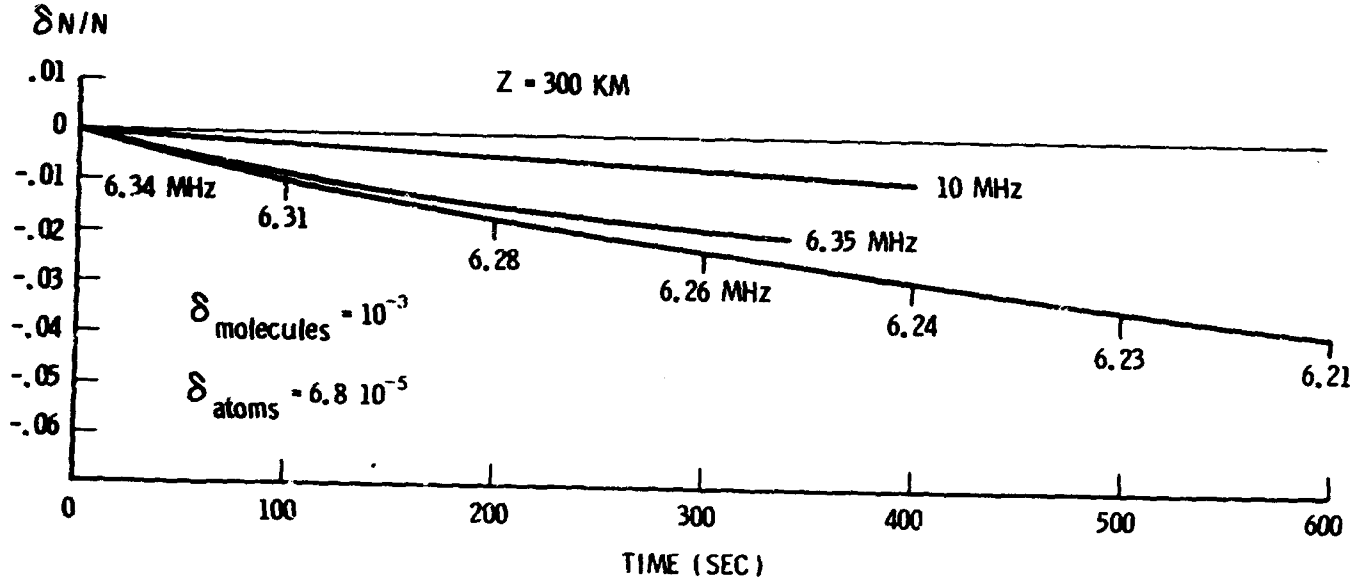

Fig.5—Fractional electron density decrease as a function of time for the indicated radiowave frequencies

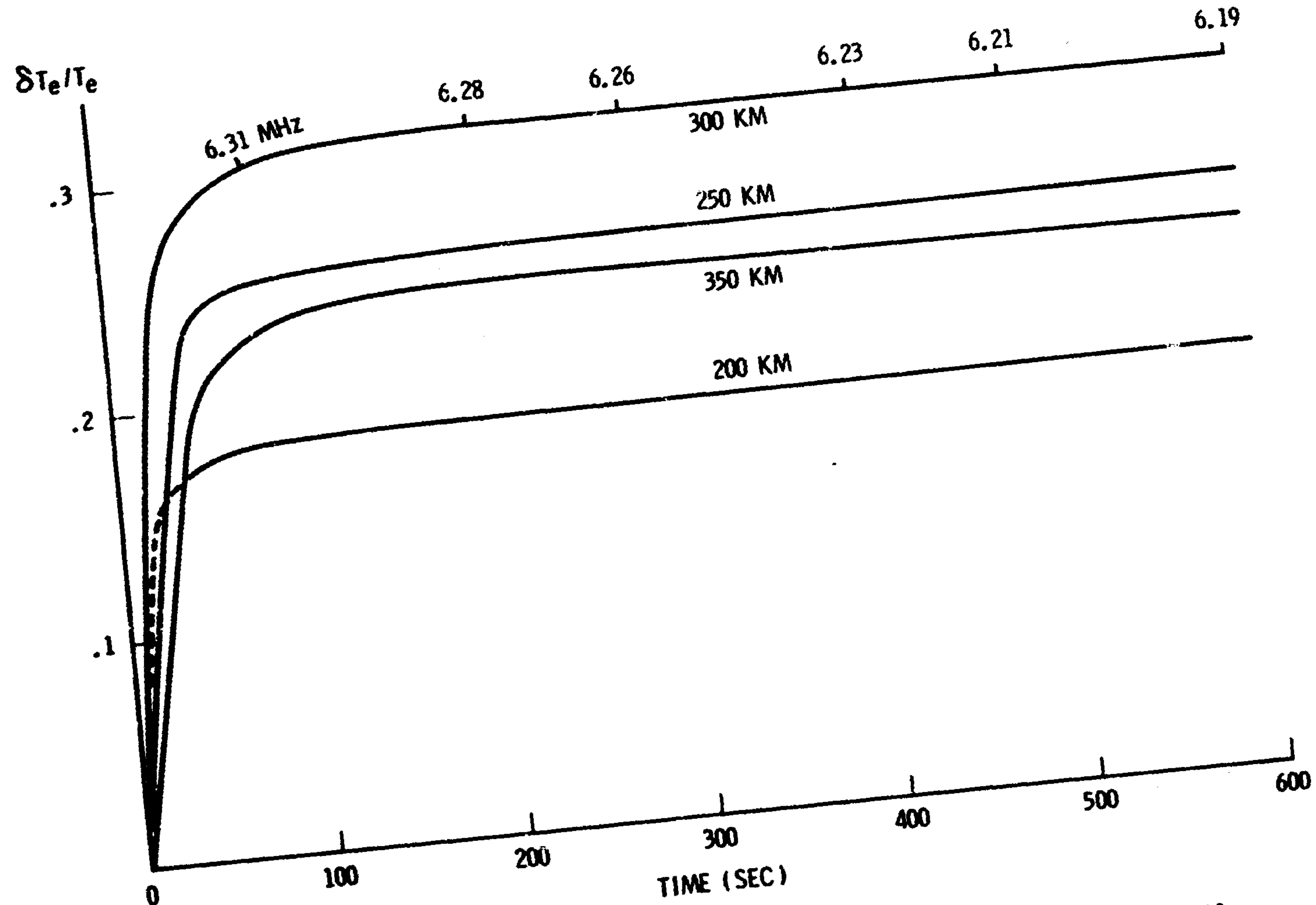

Fig. 6—Fractional electron temperature increase as a function of time for the indicated altitudes. The radiowave frequency is programmed within one percent of critical.

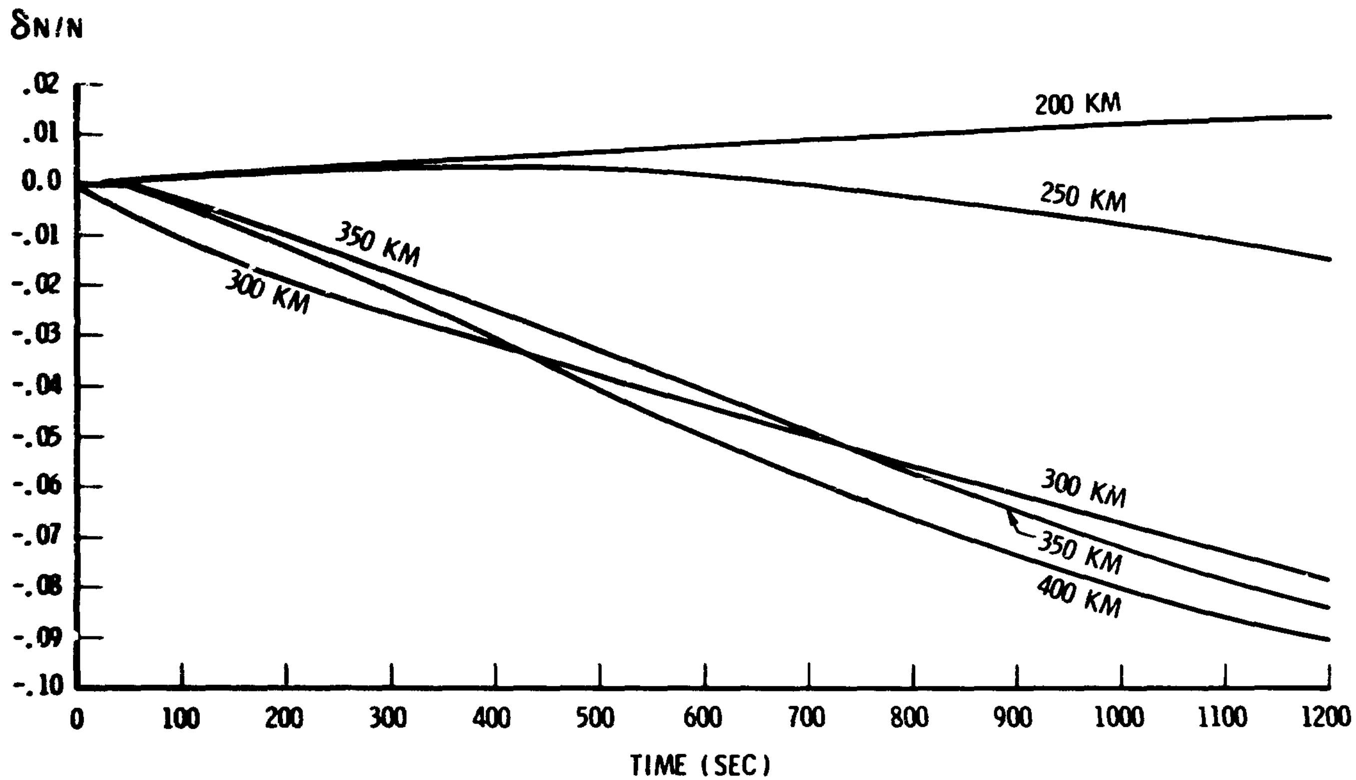

Fig. 7—Fractional electron density decrease as a function of time for the indicated altitudes. The radiowave frequency is programmed within one percent of critical

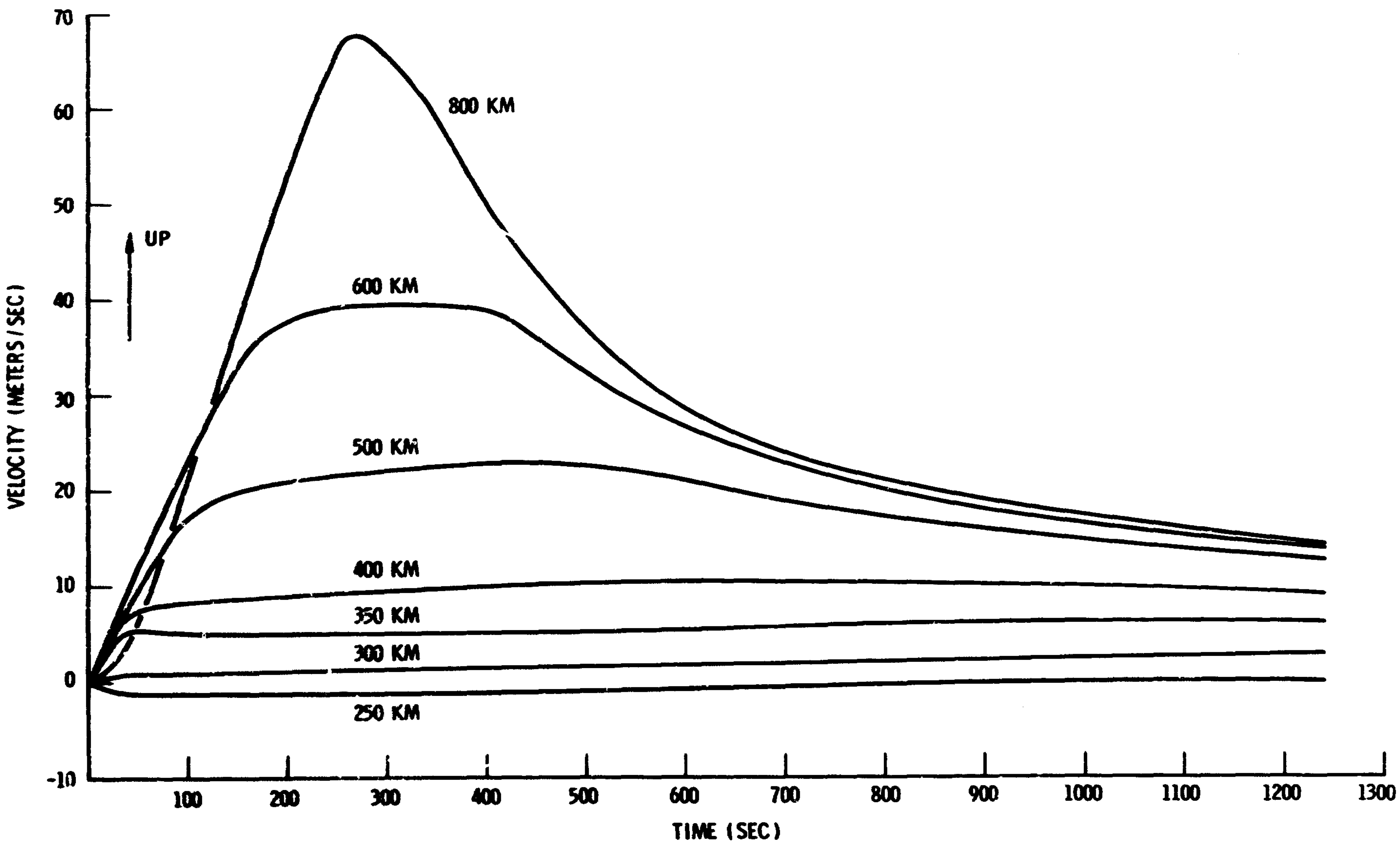

Fig. 8—Velocities induced in the ionosphere due to heating process